AD 158630

Armed Services Technical Information Agency

ARLINGTON HALL STATION
ARLINGTON 12 VIRGINIA

FOR MICRO-CARD CONTROL ONLY

1 OF 1

UNCLASSIFIED

AD No. 158630

ASTIA FILE COPY

158630

10

BRL

FC

TECHNICAL NOTE NO. 1178

MARCH 1958

ON RESONANCE PHENOMENA AND SHORT RANGES IN MORTAR FIRE

C. L. POOR

DEPARTMENT OF THE ARMY PROJECT NO. 5B03-03-001

ORDNANCE RESEARCH AND DEVELOPMENT PROJECT NO. TB3-0108

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

TECHNICAL NOTE NO. 1178

MARCH 1958

ON RESONANCE PHENOMENA AND SHORT RANGES IN MORTAR FIRE

C. L. Poor

This paper was presented at the 8th Tripartite Research Conference on Armaments, Explosives, and Propellants, and will be published in the proceedings of that meeting.

The report was presented at the Fin-Stabilizer Ammunition Symposium 16-17 Oct. 1957 at Picatinny Arsenal and is being published in the proceedings of the symposium.

Department of the Army Project No. 5B03-03-001
Ordnance Research and Development Project No. TB3-0108

A B E R D E E N   P R O V I N G   G R O U N D,   M A R Y L A N D

B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

TECHNICAL NOTE NO. 1178

CLPoor/mmv
Aberdeen Proving Ground, Md.
March 1958

ON RESONANCE PHENOMENA AND SHORT RANGES IN MORTAR FIRE

ABSTRACT

The occurrence of occasional short ranges in mortar fire has long plagued the designers of ordnance materiel and impaired the utility of mortars in combat. Despite the existence of a well-developed theory of motion and the availability of means for reliable measurement of the principal aerodynamic properties of new shell, sporadic short rounds continue to occur with contemporary designs.

The principal purpose of this paper is to review the American effort toward elucidation of the causes of short ranges in mortar fire, and to present the author's conclusions as to how sporadic shorts may be eliminated by suitable design and quality control precautions. It is apparent that full understanding of the non-linear phenomena which presumably operate when a round becomes a "short" is not necessary. "Shorts" may be eliminated by satisfying four conditions, conditions which serve to guarantee that the flight is describable by linearized aerodynamic theory. The extent to which current knowledge permits detailed satisfaction of all conditions is discussed and the need for further reliable measurements is pointed out.

INTRODUCTION

The occurrence of occasional short ranges in mortar fire has long plagued the designers of ordnance materiel and impaired the utility of mortars in combat. Despite the existence of a well-developed theory of motion and the availability of means for reliable measurement of the principal aerodynamic properties of new shell, sporadic short rounds continue to occur with contemporary designs.

The principal purpose of this paper is to review the American effort toward elucidation of the causes of short ranges in mortar fire, and to present the author's conclusions as to how sporadic shorts may be eliminated by suitable design and quality control precautions.

The experimental and theoretical work on which this review is based was conducted by personnel of the Exterior Ballistics Laboratory of the Ballistic Research Laboratories or by other U. S. groups at our request. To reduce the volume of the review to manageable proportions, I have been forced to eliminate much work of historical significance and have failed to give proper credit to the many people and groups of people who have contributed to our understanding of the phenomena. I have also resorted to a certain amount of oversimplification. As far as possible, the treatment is non-mathematical. Details on the relevant mathematics may be obtained from the references.

BACKGROUND OF THE PROBLEM

There have been two main lines of approach to the problem of short ranges. Both recognize the fact that the causes of short ranges are aerodynamic and that catastrophic short ranges must be associated with extreme yawing motion.

The first approach seeks to study the aerodynamic characteristics of mortar ammunition at large yaw amplitudes and to describe in sufficient detail the growth of the yawing motion. Here the hope is that we can understand completely the complicated non-linear mechanics of the large amplitude motion, and, given the initial conditions at the beginning of the trajectory, can compute the point of fall. Success in such an attack depends upon elaborate studies in non-linear mechanics and obtaining a prohibitively large amount of data on the aerodynamics of the shell in question.

The second approach, which has apparently proven far more successful, seeks to apply the results of linear theory to design of mortar systems, designed against the occurrence of yaws in flight large enough to cause significant non-linear phenomena. If we can guarantee that along the whole trajectory the shell yaw never exceeds some small value, say five degrees, we should be able to apply the well-known stability criteria of the linearized theory of motion. If, finally, the linearized predictions show that the yawing motion cannot grow beyond the bounds of validity of the theory, we should be able to state confidently that the design will be free of short range phenomena. Should the computations show that the yaw does grow beyond the range of validity of the linearized theory, there is the possibility of short ranges. Examining this possibility in detail involves a return to the first approach. An alternative, and more desirable approach, would be so to modify the shell design as to eliminate large yaw amplitutes altogether.

It is the thesis of this paper that we can, in fact, design against large yaws, and so guarantee against short rounds.

CONDITIONS FOR ABSENCE OF SHORT ROUNDS

Conditions which must be met to guarantee that flight is describable by linearized theory are:

1. Initial yaw due to launching disturbances must be sufficiently small.

2. Initial damping of the motion must be sufficient.

3. Resonant amplification of the effects of fin misalignment must not occur to such an extent as to initiate non-linear instability.

4. Spin rate must be low enough to avoid magnus instability.

STATUS OF CURRENT KNOWLEDGE

In order to perform the linearized theory design process required to meet the four conditions outlined above, we must know enough about the aerodynamics of the proposed designs to make accurate estimates and enough about the dynamics of the situation to make accurate trajectory calculations. Most important, we must be able to guarantee that the yaw is small enough from the beginning of the flight to make our analysis valid.

Several years ago, U. S. trench mortar designs could not meet the first condition for rational linearized theory design. The launching yaws were too big. Experiments on the effect of bore clearance on the launching characteristics of a typical mortar shell, conducted in the Ballistic Research Laboratories Transonic Range (Reference 1), showed that under ideal conditions, initial yaws of the order of 30 degrees could be expected. Linear theory analysis clearly could not be applied to such cases. Reducing the windage from the "service" value to zero reduced launching yaw to about 4 degrees.

Early in 1952 under the sponsorship of the U. S. Army Ordnance Corps, the Budd Company, of Philadelphia, undertook the development of an improved mortar. The principal effort of the company during the life of their contract has been devoted to obtaining means of launching mortar shell from smooth bore tubes with satisfactorily low initial yaw. The success of the work may be judged from the latest report to the Steering Committee established for this project (Reference 2). Launching yaws of about 4 degrees can be obtained reliably through close windage tail structures and the use of a plastic obturating ring on the body of the shell. The ring provides ample clearance for loading the round in the conventional way. On firing, the ring expands, centering the round in the tube, and providing a reliable gas seal. The benefits are two-fold, a substantial reduction in initial yaw, and an appreciable increase in muzzle velocity with a given propellant charge.

From the reported results of the work of the Budd Company, and from the results of many measurements of the aerodynamic characteristics of a wide variety of fin-stabilized rounds in the wind tunnels and spark ranges, I conclude that it is now possible to design mortar systems which meet the first of my four conditions. Initial yaw can be made small enough to guarantee the validity of linearized theory - small enough so that we can now hope to understand the subsequent motion in detail.

Now, I hasten to warn you that satisfying one condition is not enough. A mortar shell launched with small initial yaw may fly erratically, may still exhibit sporadic short rounds. Many flights of mortar shell have been observed in which the severe initial yaw damped down to very small levels, but in which something went very wrong later on. Short round behavior growing from small initial yaw has also been observed in firings of the new Budd Company designs, where the initial yaw was observed and known to be small.

Where do we stand on the balance of the four conditions? I know of no experiments in the U. S. in which all four have been clearly satisfied simultaneously. But, I am sure they all can be.

The second condition, satisfactory initial damping of the yawing motion, is almost trivial. Every normal fin-stabilized shell we have tested that shows satisfactory static stability in flight shows strong damping of the yawing motion, provided the axial spin is not too great. Damping to half amplitude in three to five cycles of the yawing motion is typical of fin-stabilized shell with low roll rates. So it is not here that we need look for our troubles.

Resonance is, however, strongly suspect. The short round phenomenon is a rare thing. An occasional round, apparently just like its normal counterparts, starts out normally, but fails to reach normal range. Something happens to increase the drag in flight far above the normal level.

Thus, we have been led to examine carefully the expected roll histories of mortar shell in flight. Through experiments in the Ballistic Research Laboratories Transonic Range (References 1, 3, 4, 5), a body of knowledge of the rolling characteristics of fin-stabilized rounds has been accumulated. Computations, using an analogue computer, of the spin variation of a typical mortar shell, have been compared to observations of the spin in flight using a spin sonde fuse. The flight measurements, made by the Diamond Ordnance Fuze Laboratory, are in excellent agreement with the linearized theory calculations, as reported in Reference 6.

Thus, it appears that we can make reliable calculations of the spin history along the trajectory for non-pathological cases at least. If we have satisfied the first two conditions for absence of short rounds, the linear theory of motion should apply, and we should be able to check on whether or not our design is safe on the two remaining criteria, both of which involve the spin.

Let us summarize where we stand so far. With new techniques of obturation we can launch our shell with small yaws. Satisfactory static stability guarantees high damping in pitch, so the second condition, adequate initial damping of the motion, is automatically satisfied.

Nevertheless, sporadic short range behavior has been observed with rounds known to be launched with small yaws, for which the stability appears more than adequate, and which were built with zero fin cant, so that the spin would be expected to be very small indeed. Can we explain the phenomenon, and, if so, is there a simple, reliable engineering fix to protect us against its occurrence?

THE EXPECTED SPIN OF MORTAR SHELL

The spin-yaw resonance phenomenon is by now relatively well understood. Routine reduction of the observations on fin-stabilized rounds in the Ballistic Research Laboratories spark ranges takes into account the effects of asymmetry and the tricyclic motion characteristic of spin-yaw resonant phenomena. Computations of the behavior of fin-stabilized shell passing through resonance in flight have been made on analogue computers and have shown excellent agreement with precision free flight measurements (References 7, 8, and 9).

Is it probable that spin-yaw resonance is a cause of short ranges for shell with adequate stability? To answer this question, we must look at the expected spin histories in some detail, and examine under what circumstances passage through resonant spin can be expected to be damaging to the flight.

First, as to the nature of the spin histories. The spin histories of Reference 6 are reproduced in Figures 1, 2, 3, and 4. The first figures show the spin rate as a function of time along the trajectory and exhibit the satisfactory agreement between the experimental results and the computations based on linearized theory and the Transonic Range measurements of Reference 4. Note the relatively large range of variation of spin, caused by round-to-round variation in the effective cant or twist of the tail assemblies. This variation is characteristic of mortar shell, and is an inevitable consequence of the small damping in roll with fins that do not extend beyond body diameter.

The fourth figure is more valuable in understanding the possibilities. Here we have plotted the non-dimensional spin rate, in radians per caliber, against distance along the trajectory. Also shown is the pitch frequency, in the same units. If the roll rate should coincide with the pitch rate for an appreciable distance, we have the possibility of roll-pitch resonance, with the further possibility, if the pitch misalignment of the tail is great enough, of non-linear divergence. We must have both accidents for trouble, a resonant roll rate, and enough other misalignment to cause large yaws. In Reference 10, the linear aerodynamics of the situation are discussed.

Now rounds with the spin histories of those discussed so far should be amply safe against resonance. They go through quickly and, in those parts of the trajectory where the non-dimensional spin is relatively constant, are spinning at rates far higher than resonance.

But what of the standard mortar rounds, with nearly zero fin cant? Here the spins should be below the resonant rate, but will they really be? Now I cannot avoid numbers. Let us use the same shell, the T53E1, which is more or less similar to recent U. S. designs in 60mm and 81mm sizes. The pitch rate of the round at sea level and subsonic velocities is about 0.007 radians per caliber. To match this spin exactly near the summit of a 45 degree trajectory would require an effective fin cant of 0.0031 radian or about 0.2 degrees. With a fin cant of 0.3 degrees, the 45 degree trajectory would have spins safely above resonance, 0.1 degrees would put us safely below.

The spread about the nominal zero fin cant to be expected of production rounds can be inferred from several sources. The data I have shown for the 105mm T53E1 indicate an extreme spread of about 1 degree. Measurements on the tails of 600 rounds of 81mm M-56 shell show a variation of about 1 degree. Finally, unpublished spin sonde firings of some 60 rounds of 81mm M-56 shell conducted by the Development and Proof Services of Aberdeen Proving Ground for Mr. Zaroodny of my laboratory show spin rates at the summit of 50 degree trajectory varying from nearly zero to .048 radians per caliber. The extreme spread in effective fin cant to explain these results is again about 1 degree.

Thus, we can expect that shell with tails designed for zero cant will have spin history distributions which will certainly include the resonant frequency. With a spread in fin cant of the order observed on representative samples, the chance that a given shell will stay within 5% of resonance for an appreciable time is .04. The chance that these resonating shell will have sufficient trim misalignment to cause non-linear divergence depends on manufacturing tolerances, possible accidental bending in handling, etc., and is difficult to estimate. I have guessed that the net probability of a short round from this cause is between .01 and .001, not too far removed from practical experience with representative mortar shell.

As further evidence, the same unpublished spin sonde firings, which were contaminated with severe launching yaws, contained some 11 rounds which came and stayed uncomfortably close to resonant spins. Of these, three fell short. Two other shorts were observed, but these were badly launched and had persistent large yaws from the beginning of flight, and so fell outside this class of "reasonably launched" shell I am discussing.

Thus, I conclude that roll-pitch resonance is a possible cause of sporadic short ranges, the most likely cause for reasonably launched shell. We can't produce resonant shorts to order - the control of fin cant required is too close. We should be able to avoid them altogether in practice by using relatively high fin cant, sufficiently high so that within reasonable manufacturing tolerances there is no possibility of resonant shorts.

If we do this, we should be out of the woods. But there is another danger about which we know relatively little. This is my fourth condition, the avoidance of Magnus instability.

MAGNUS INSTABILITY

The possibility of destabilizing a properly damped fin-stabilized shell by the Magnus moment associated with relatively high axial spin is well known. Engineering estimates are hampered by the complete lack of an adequate aerodynamic theory for the Magnus moment and by the experimental difficulties attendant on wind tunnel measurements. The wind tunnel data available (References 11, 12, 13) are too crude for reliable estimates at small yaws. For the 60mm T-24, the wind tunnel tests of Reference 13 and the spark range firings of Reference 5 both give indications of Magnus instability at spin rates of about 0.1 radians/caliber, spin rates easily reached with a 4 degree cant of the fin trailing edge, in high angle fire.

Flight tests conducted by the Budd Company on well-launched 60mm shell with varying fin cants gave sporadic short rounds for fin cants below 2 degrees. As the fin cant was increased above 2 degrees the sporadic shorts disappeared, as predicted by the roll-pitch resonant theory outlined above.

While the resonant short rounds of the 60mm mortar shell T-24 have apparently been eliminated by the Budd Company redesign, the possibility of short ranges due to Magnus moment has not been completely eliminated. In high angle fire, shorts might still be expected.

Thus, my fourth condition may not have been satisfied for the one round on which most work has been done. The 60mm T-24 is a relatively short, fat shell. Unfortunately, no fully reliable Magnus moment data are available on the longer 81mm T-28 and 105mm T-53. These designs may, in fact, be satisfactorily stable for all flight conditions, but precision Magnus data are required to establish the position and to determine the upper limit of the permissible fin cant.

CONCLUSION

When reliable data on Magnus moment are available, we should be able to design trench mortars and their associated ammunition to be completely free of short range behavior. Enough is known today to permit avoiding excessive initial yaw. Enough is known to permit choosing a lower limit of fin cant as required to avoid resonant instability. We need still to know the upper limit on fin cant imposed by Magnus effects. If, as appears to be the case with the 60mm T-24, this limit is too low, redesign is needed, with longer tails to raise the damping in pitch and increase the spin level for Magnus instability to sufficiently high levels to permit reasonable limits on manufacturing tolerances in tail cant. A program of firings in the Ballistic Research Laboratories Transonic Range is currently in hand to obtain reliable Magnus moment data. If it is successful, rational design of fin-stabilized mortar shell, free from short round behavior, should be assured in the future.

C. L. Poor

C. L. POOR

REFERENCES

1. MacAllister, L. C. and Roecker, Eugene T., "Aerodynamic Properties Spin and Launching Characteristics of 105mm Mortar Shell T43E1 with Two Types of Fins", Ballistic Research Laboratories Memorandum Report No. 618, September 1952, Unclassified.

2. Sixth Report to the Steering Committee by the Budd Company, Period 5/1/55 to 7/1/57, "81mm Mortars and Ammunition", Confidential.

3. Karpov, B. G., "Aerodynamic and Flight Characteristics of the 90mm Fin Stabilized Shell, Heat, T108", Ballistic Research Laboratories Memorandum Report No. 696, July 1953, Confidential.

4. MacAllister, L. C., "Spin and Aerodynamic Characteristics of the 105mm Shell T-131, HEAT", Ballistic Research Laboratories Technical Note No. 590, February 1952, Confidential.

5. Boyer, Eugene D., "Aerodynamic Properties of 60mm Mortar Shell, T24", Ballistic Research Laboratories Memorandum Report No. 1020, July 1956, Unclassified.

6. Bradley, J. W., "A Comparison of Measured Spin Histories of 105mm Mortar Shell T53E1 with Solutions of the Linearized Roll Equation", Ballistic Research Laboratories Memorandum Report No. 1074, May 1957, Unclassified.

7. Nicolaides, J. D., "On the Free Flight Motion of Missiles Having Slight Configurational Asymmetries", Ballistic Research Laboratories Report No. 858, June 1953, Unclassified.

8. Murphy, C. H., "Data Reduction for the Free Flight Spark Ranges", Ballistic Research Laboratories Report No. 900, February 1954, Unclassified.

9. Schmidt, Jo Ann M., "A Study of the Resonating Yawing Motion of Asymmetrical Missiles by Means of Analog Computer Simulation", Ballistic Research Laboratories Report No. 922, November 1954, Unclassified.

10. Galbraith, A. S., "On the Motion of a Slightly Deformed Projectile", Ballistic Research Laboratories Report No. 896, January 1954, Unclassified.

11. Mott, R. S., "Dynamic Measurements on the 81mm Shell T-28E6 in the National Bureau of Standards Wind Tunnel", Ballistic Research Laboratories Report No. 908, May 1954, Unclassified.

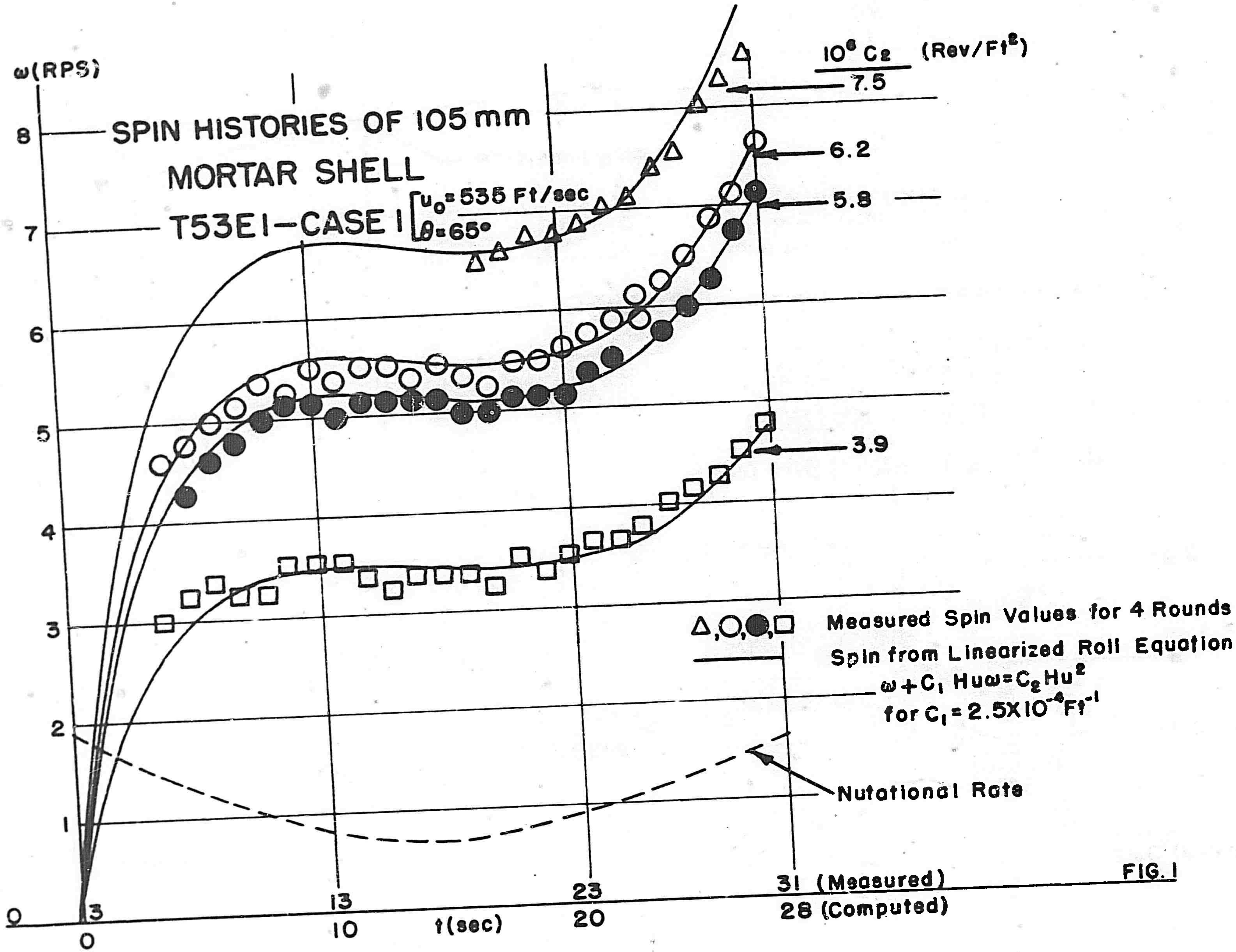
12. Zaroodny, S. J. and Mott, R. S., "Dynamic Measurements on the 81mm Shell M56 in NBS Wind Tunnel", Ballistic Research Laboratories Report No. 882, October 1953, Unclassified.

13. Kemp, W. B.,Jr. and Hayer, W. C., Jr. "Wind Tunnel Investigation of the Effect of Spin on the Aerodynamic Characteristics of a 60-Millimeter T-24 Mortar Shell with Several Tail-Fin Configurations", National Advisory Committee for Aeronautics Research Memorandum SL57C12, Confidential.

14. Murphy, C. H., "Prediction of the Motion of Missiles Acted on by Non-linear Forces and Moments", Ballistic Research Laboratories Report No. 955, October 1956, Unclassified.

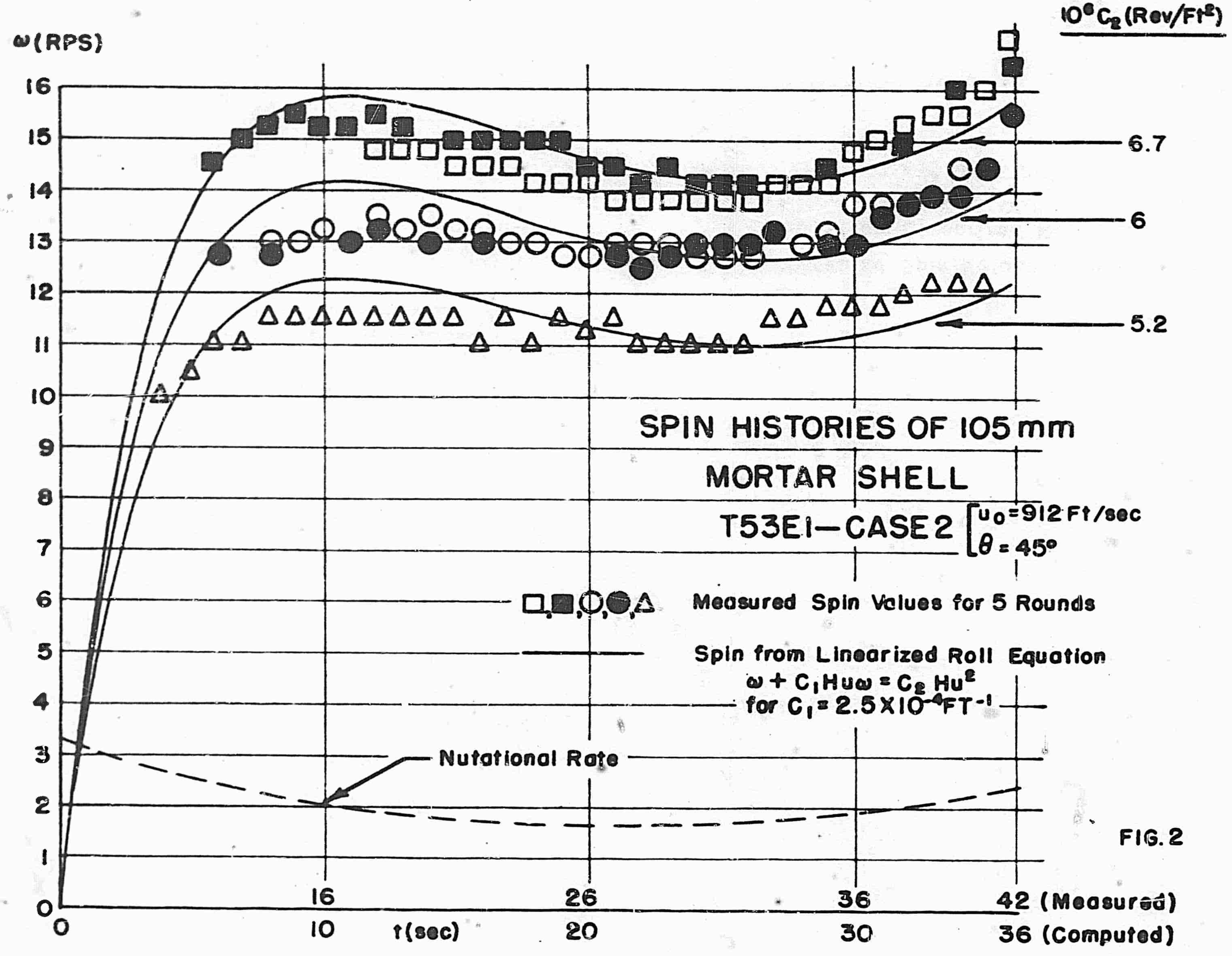
15. Murphy, C. H., "The Measurement of Non-linear Force and Moments by Means of Free Flight Tests", Ballistic Research Laboratories Report No. 974, February 1956, Unclassified.

16. Kistler, I. B., "An Application of Non-linear Theory to the Yawing Motion of Mortar Shell", Ballistic Research Laboratories Report No. 1009, March 1957, Unclassified.



ω(RPS)
SPIN HISTORIES OF 105 mm
MORTAR SHELL
T53E1—CASE I
u0=535 Ft/sec
θ=65°
10⁶ C2 (Rev/Ft²)
7.5
6.2
5.8
3.9
Measured Spin Values for 4 Rounds
Spin from Linearized Roll Equation
ω+C1 Huω=C2 Hu²
for C1=2.5X10⁻⁴Ft⁻¹
Nutational Rate
t(sec)
31 (Measured)
28 (Computed)

FIG. I



ω (RPS)
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
$10^6 C_2$ (Rev/Ft²)
6.7
6
5.2
SPIN HISTORIES OF 105 mm
MORTAR SHELL
T53E1—CASE 2 u_0=912 Ft/sec
θ = 45°
Measured Spin Values for 5 Rounds
Spin from Linearized Roll Equation
$\dot{\omega} + C_1 H u \omega = C_2 H u^2$
for $C_1 = 2.5 \times 10^{-4}$ FT⁻¹
Nutational Rate
0
16
26
36
42 (Measured)
10
t (sec)
20
30
36 (Computed)

FIG. 2

SPIN HISTORIES OF 105 mm

MORTAR SHELL

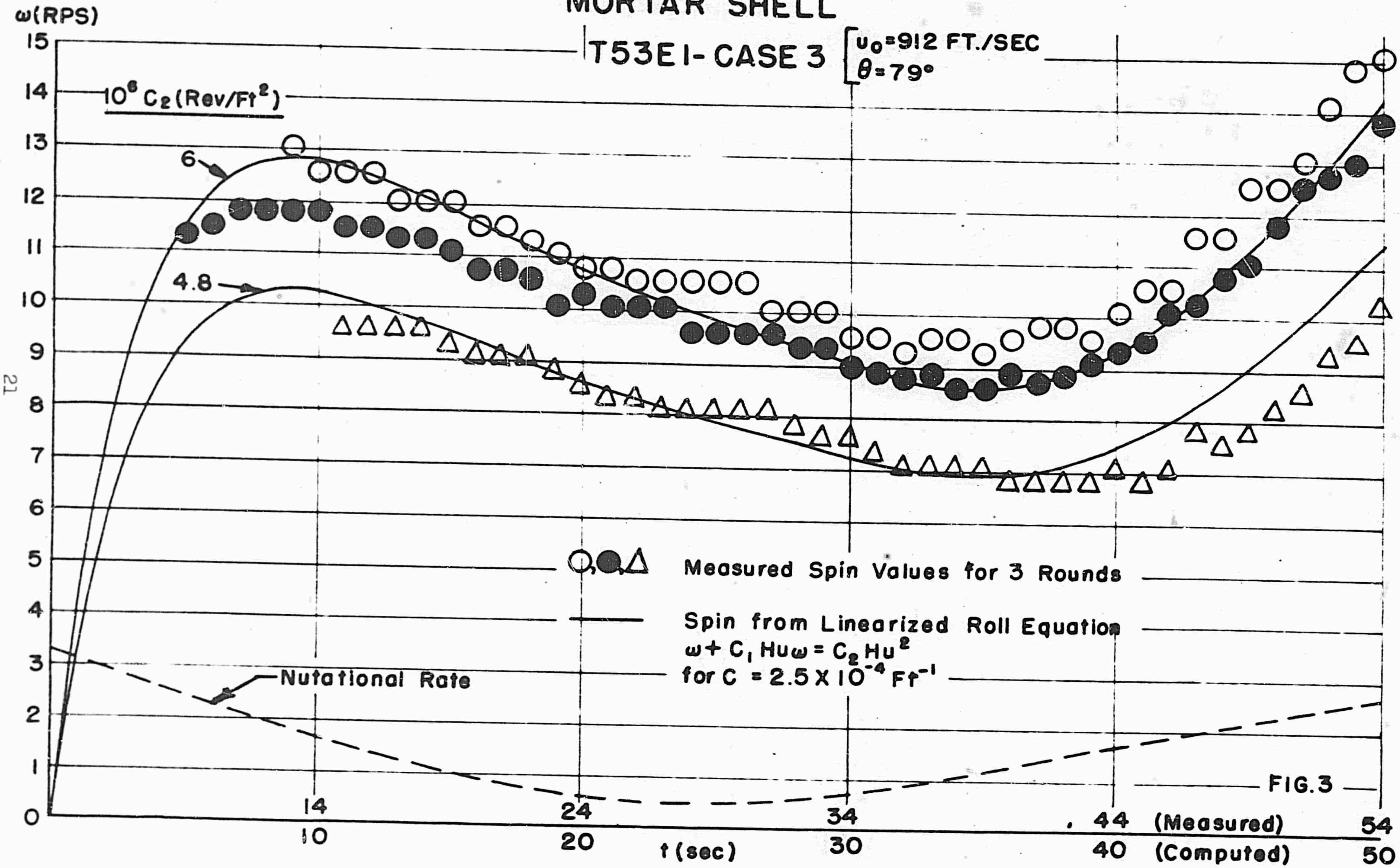


FIG. 3

SPIN HISTORIES OF 105 mm MORTAR SHELL T53E1

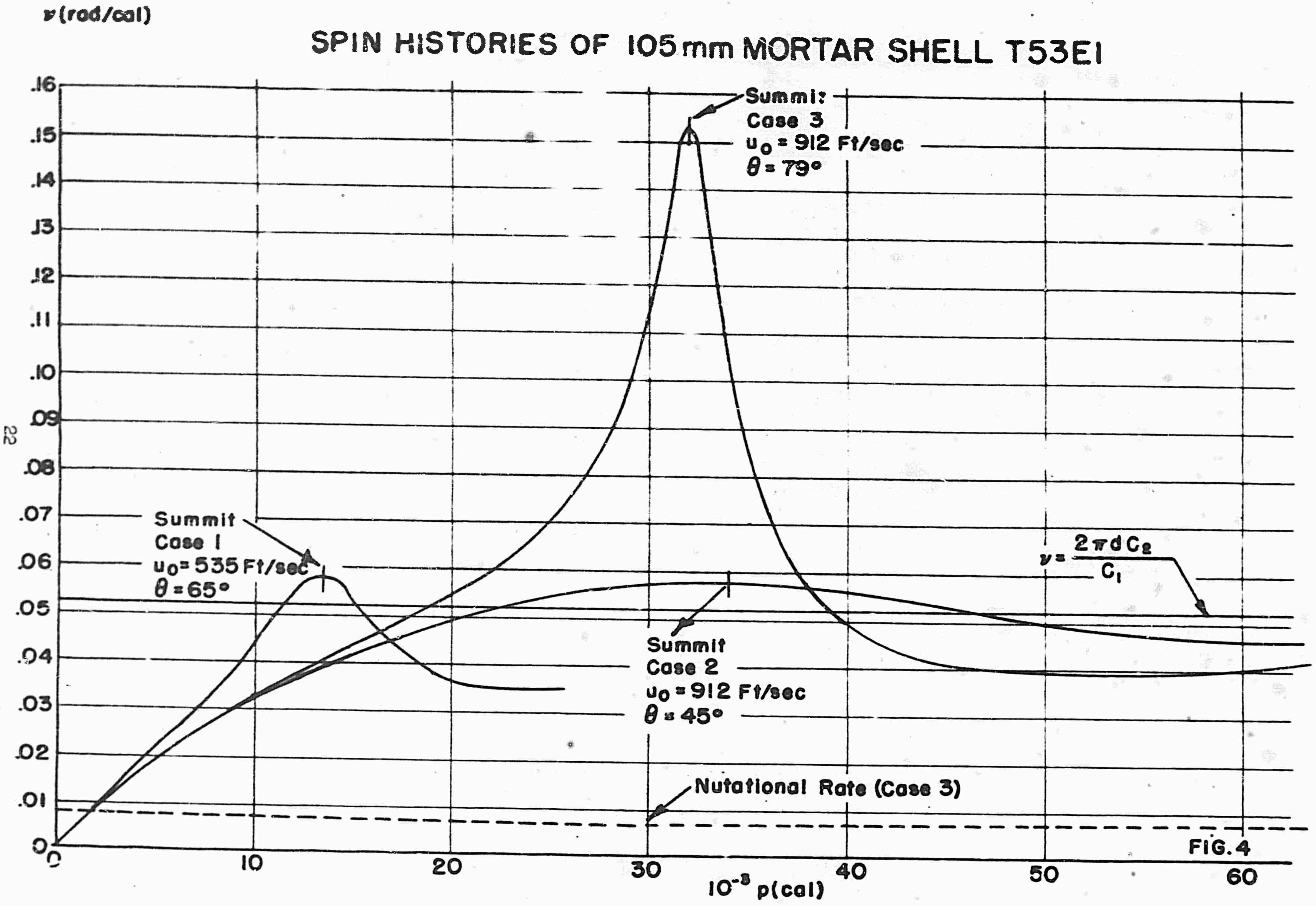


FIG. 4

DISTRIBUTION LIST

No. of Copies	Organization
2	Chief of Ordnance Department of the Army Washington 25, D. C. Attn: ORDTB - Bal Sec ORDTW
10	British Joint Services Mission 1800 K Street, N. W. Washington 6, D. C. Attn: Mr. John Izzard Reports Officer
4	Canadian Army Staff 2450 Massachusetts Ave., N.W. Washington 8, D. C.
3	Chief, Bureau of Ordnance Department of the Navy Washington 25, D. C. Attn: ReO
2	Commander Naval Proving Ground Dahlgren, Virginia
2	Commander Naval Ordnance Laboratory White Oak Silver Spring, Maryland Attn: Mr. Nestinger Dr. May
1	Superintendent Naval Postgraduate School Monterey, California
2	Commander Naval Air Missile Test Center Point Mugu, California
1	Commanding Officer and Director David W. Taylor Model Basin Washington 7, D. C. Attn: Aerodynamics Laboratory
1	Commander Naval Air Development Center Johnsville, Pennsylvania
1	Commanding Officer Naval Air Rocket Test Station Lake Denmark Dover, New Jersey
3	Commander Naval Ordnance Test Station China Lake, California Attn: Technical Library (2 cys) Aeroballistic Lab. Code 5034
4	Commander Air Research and Development Command Andrews Air Force Base Washington 25, D. C. Attn: RDTWMB
1	Commander Air Proving Ground Center Eglin Air Force Base, Florida Attn: PGTRI
1	Commander Arnold Engineering Development Center Tullahoma, Tennessee Attn: Deputy Chief of Staff, R&D
10	Director Armed Services Technical Information Agency Arlington Hall Station Arlington 12, Virginia

DISTRIBUTION LIST

No. of Copies	Organization	No. of Copies	Organization
2	U. S. Atomic Energy Commission Sandia Corporation P. O. Box 5400 Albuquerque, New Mexico	1	Assistant Secretary of Defense (R&E) Department of the Army Washington 25, D. C. Attn: Director/Ordnance
1	Director National Advisory Committee for Aeronautics 1512 H Street, N. W. Washington 25, D. C.	1	Chief of Staff (R&D) Department of the Army Washington 25, D. C. Attn: Director/Dev. Combat Materiel Command
1	Director National Advisory Committee for Aeronautics Ames Laboratory Moffett Field, California Attn: Dr. A. C. Charters Mr. H. J. Allen	2	Commander Army Rocket and Guided Missile Agency Redstone Arsenal, Alabama Attn: Technical Library, ORDXR-OTL Of Interest to: T. G. Reed, ABMA
3	Director National Advisory Committee for Aeronautics Langley Memorial Aeronautical Laboratory Langley Field, Virginia Attn: Mr. J. Bird Mr. C. E. Brown Dr. Adolf Busemann	3	Commanding Officer Picatinny Arsenal Dover, New Jersey Attn: Samuel Feltman Ammunition Labs.
1	Director National Advisory Committee for Aeronautics Lewis Flight Propulsion Lab. Cleveland Airport Cleveland, Ohio Attn: F. K. Moore	1	Commanding General Frankford Arsenal Philadelphia 37, Penna. Attn: Reports Group
1	Director, JPL Ord Corps Installation Department of the Army 4800 Oak Grove Drive Pasadena 3, California Attn: Mr. Irl E. Newlan Reports Group	1	Commanding Officer Diamond Ordnance Fuze Lab. Washington 25, D. C. Attn: ORDTL - 06.33
		1	Commanding Officer U. S. Army Chemical Warfare Laboratories Army Chemical Center, Md.

DISTRIBUTION LIST

No. of Copies	Organization	No. of Copies	Organization
1	The Johns Hopkins University Operations Research Office 6935 Arlington Ave. Bethesda, Maryland	1	University of Southern California Engineering Center Los Angeles 7, California Attn: Mr. H. R. Saffell Director
2	Armour Research Foundation Illinois Institute of Technology Technology Center Chicago 16, Illinois Attn: Mr. W. Casier Dr. A. Wundheiler	1	United Aircraft Corp. Research Department East Hartford 8, Conn. Attn: Mr. C. H. King
2	Applied Physics Laboratory 8621 Georgia Avenue Silver Spring, Maryland Attn: Mr. George L. Seielstad	1	Wright Aeronautical Division Curtiss-Wright Corporation Wood-Ridge, N. J. Attn: Sales Dept. (Gov't)
1	Aerophysics Development Corp. P. O. Box 657 Pacific Palisades, California Attn: Dr. William Bollay	1	Professor George Carrier Division of Applied Sciences Harvard University Cambridge 38, Massachusetts
1	Cornell Aeronautical Lab., Inc. 4455 Genesee Street Buffalo, New York Attn: Miss Elma T. Evans Librarian	1	Professor Clark B. Millikan Guggenheim Aeronautical Lab. California Institute of Technology Pasadena 4, California
1	CONVAIR Division of General Dynamics Corporation Ordnance Aerophysics Laboratory Daingerfield, Texas Attn: Mr. J. E. Arnold	1	Dr. A. E. Puckett Hughes Aircraft Company Florence Avenue at Teal Street Culver City, California
1	M. W. Kellogg Company Foot of Danforth Avenue Jersey City 3, New Jersey Attn: Miss E. M. Hedley	1	Dr. L. H. Thomas Watson Scientific Computing Laboratory 612 West 116th Street New York 27, New York
1	Technical Documents Services Willow Run Laboratories University of Michigan Willow Run Airport Ypsilanti, Michigan Attn: Mr. J. E. Corey		

ARMY-APG, Md.-D